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Carbon budget of Ontario's managed forests and harvested wood products, 2001–2100

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ABSTRACT

Forest and harvested wood products (HWP) carbon (C) stocks between 2001 and 2100 for Ontario's managed forests were projected using FORCARB-ON, an adaptation of the U.S. national forest C budget model known as FORCARB2. A fire disturbance module was introduced to FORCARB-ON to simulate the effects of wildfire on C, and some of the model's C pools were re-parameterized using data from Canadian forests. Forest C stocks were estimated using allometric equations that represent the relationships between C and net merchantable volume and forest age based on forest inventory statistics. Other pools were included using results from ecological studies related to forest inventory variables. Data from future forest development projections adopted in approved management plans were used as model input to produce forest C budgets for the province's Crown forest management units. The estimates were extended to other types of managed forests in Ontario: parks, measured fire management zones, and private forest lands. Carbon in HWP was estimated in four categories: wood in use, wood in landfill, wood burned for energy, and C emitted by wood decomposition or burning without energy generation. We projected that the C stocks in Ontario's managed forests and HWP (in use and in landfills) would increase by 465.3 Mt from 2001 to 2100, of which 47.9 Mt is from increases in forest C and 417.4 Mt is from HWP C.

1. Introduction

The most recent climate change assessment report from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007a) stated that global warming is unequivocal and is very likely due to anthropogenic-induced increases in atmospheric greenhouse gases. The report also indicates that mitigating climate change by reducing greenhouse gas emission can reduce or delay most effects in the medium and long term (IPCC, 2007b).

Carbon dioxide (CO_2) is an important greenhouse gas, the anthropogenic release of which is mainly through fossil fuel use and deforestation in the tropics. Over a specific time period and depending on their age, management and disturbance, forests can be net emitters of CO_2 to the atmosphere, making climate change worse, or they can be a potential means to mitigate climate change. Dixon et al. (1994) estimated that the world's forests contained up to 80% of all aboveground and about 40% of all belowground (soil, litter, and roots) terrestrial carbon (C). Thus, forestry-related mitigation activities have great potential for both reducing emissions and increasing removals at low cost (IPCC, 2007c). These mitigation options include reducing C emissions caused by deforestation, enhancing C sequestration rates in existing and new forests through forest management, and substituting wood for more energy-intensive materials and fossil fuels (IPCC, 2007c).

Forest harvesting removes merchantable wood volume, which is processed into various types of harvested wood products (HWP) that retain C for varying lengths of time. Many studies show that the global C stock in HWP is large and increasing (Kellomäki and Karjalainen, 1996; Winjum et al., 1998; Apps et al., 1999; Skog and Nicholson, 2000; Pingoud et al., 2003; IPCC, 2006; Chen et al., 2008; Skog, 2008). Ontario's 70.2 million ha of forests account for 17% of Canada's total and about 2% of the world's forest, covering a land area equivalent in size to the landmasses of Germany, Italy, and the Netherlands combined (OMNR, 2007). Ontario is also an important global HWP producer, providing 14.2% of the total harvested roundwood in Canada between 1951 and 2006 (www.nfdp.ccfm.org/compendium/data/2008_06/tables/com51e.pdf, accessed August 12, 2008). Thus, quantifying Ontario's forests and HWP C stocks and understanding how these vary in time is needed to

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support the development of a comprehensive C budget for Canada and the global forest sectors.

Others have estimated Ontario's historical forest C stocks (Peng et al., 2000; Liu et al., 2002) using forest inventory data derived from the National Forest Biomass Inventory (Bonnor, 1985). In these studies, Ontario forests were divided into four ecoregions (sub-actic, boreal, temperate and moderate temperate). We improved this coarse spatial resolution by using the Ontario Forest Resource Inventory for the 46 forest areas managed for timber production (forest management units). Each unit has an official forest management plan, which is updated every five years (www.appefmp.mnr.gov.on.ca/eFMP/home.do?language=en, accessed October 19, 2009). Using these data enabled our results to be consistent with existing forest volume and area statistics. There is also a gap in estimating current and predicting future forest C stocks for this province. As a result, the goal of our study was to project current and future forest C as well as C stocks in HWP from Ontario. Our objectives were to: (i) connect forest C budget projection to planned forest management, (ii) provide improved estimates of current Ontario forest C stocks using more recent data, and (iii) project future forest and HWP C stocks for the managed forests in Ontario.

2. Methods

Process modeling and empirical modeling are the two main approaches used for forest C accounting. Process models are used to estimate forest C budgets based on physiological processes, e.g., CO_2 converted into biomass by photosynthesis, CO_2 emitted through respiration, and C transferred from living biomass to dead organic matter and emitted by decomposition. Their complexity is an advantage because, in principle, they can reproduce the complex dynamics of forest ecosystem and could be used to project how environmental conditions affect forest C stocks (Amthor et al., 2001; Van Oijen et al., 2005). However, these models likely include many parameters and need large amounts of site-specific data related to ecosystem characteristics, such as soil moisture and fertility, air temperature, and precipitation (Kimball et al., 1997; Liu et al., 1999; Amthor et al., 2001), for which data may not be readily available. These models also often produce output values that may be of little interest to forest managers, such as CO_2 exchange rates between ecosystem and the atmosphere as well as gross primary production (Foley et al., 1996; Kimball et al., 1997; Liu et al., 1999; Amthor et al., 2001). The complexity and the need for large amounts of field data also make evaluating the results difficult, and most process models have only been tested over a limited set of conditions. Thus, these models are less practical to use for estimating large-scale forest C (Gilmanov et al., 1997; Heath and Joyce, 1997; Van Oijen et al., 2005; Pinjuv et al., 2006).

In contrast, the strength and weakness of empirical models lie in the use of empirical relationships between the size of C pools and merchantable wood volume or stand age derived from forest resources inventory and other field measurements (Heath and Joyce, 1997; Smith and Heath, 2004; Thürig et al., 2005; Pinjuv et al., 2006; Schmid et al., 2006). Although they require only simple inputs, these models can provide efficient and accurate quantitative estimation (Thürig et al., 2005; Muukkonen and Mäkipää, 2006), and their results can be verified by converting present and future forest inventory information to C data for various forest C pools (Birdsey, 1992). In addition, empirical models can be easily incorporated into diversified management analysis and silvicultural treatments for use in forest management planning (Peng et al., 2002; Schmid et al., 2006), making them more practical. However, the use of constant relationships between input data and model outputs in such models, which normally incorporate few physiological processes and ignore factors such as the changing global climate, can result in other types of uncertainties in the output (Thürig et al., 2005; Peng et al., 2002; Pinjuv et al., 2006; Schmid et al., 2006).

2.1. Structure of FORCARB-ON

2.1.1. Forest C estimation in FORCARB-ON and FORCARB2

Resource inventories for forests managed for timber production are readily available in Ontario (OMNR, 2000). These forests have also been projected into the future by considering various management objectives in the official forest management plans. Thus, using an inventory-based empirical model to estimate forest C stocks for managed forests in Ontario is a practical approach. FORCARB-ON is primarily an empirical forest C model and was adapted from the U.S. national forest C budget model, FORCARB2 (Heath et al., in press) for use in Ontario. Developed by the USDA Forest Service (Plantinga and Birdsey, 1993; Heath, 2000), FORCARB2 has been used to generate regional and national-scale estimates of C stocks in U.S. forests and HWP (Heath and Birdsey, 1993a; Birdsey and Heath, 1995; Smith and Heath, 2004), including analyses for international negotiations (for example, the 2001 U.S. submission *on Land Use, Land Use Change, and Forestry* to the *United Nations Framework Convention on Climate Change* (U.S. Department of State, 2000)). For several years, FORCARB2 produced the estimates used for reporting official U.S. net greenhouse gas emissions and sinks resulting from the uses and changes in land types and forests (e.g., see USEPA, 2004), and a variant continues to be used.

FORCARB2 and FORCARB-ON estimate forest ecosystem C stocks in six C pools: live trees (above- and belowground), standing dead trees (above- and belowground), down dead wood (logs and branches $\geq$76 mm diameter as well as stumps), understory vegetation, forest floor (dead organic matter above the mineral soil horizon, including branches and logs <76 mm diameter, litter, and humus), and soil (Smith and Heath, 2008).

Empirical relationships between C densities and merchantable volume density or forest age by species groups were developed and applied, similar to FORCARB2 coefficients described in Smith et al. (2004) (Table 1). Following Smith et al. (2003, 2006), estimates of live tree and standing dead tree C stocks were based on net merchantable volume. Estimates of down dead wood were based on relationships with live tree biomass that rely on factors such as mortality rates of live trees, ratios of down dead wood C to live tree C, and down dead wood decay factors (following Woodbury et al., 2007). Forest floor, and understory vegetation C pools were estimated based on stand age, following Smith et al. (2006), Birdsey (1996), and Woodbury et al. (2007). Soil C was all organic C (excluding roots) in mineral soil to 1 m depth, estimated using forest area and soil C density based on forest region and forest type, following Heath and Smith (2000) and Heath et al. (2001).

Similar to FORCARB2, FORCARB-ON can be used to estimate HWP C stocks and emissions for four end-use categories, including (1) products in use (*in use*), (2) products and processing residues disposed of in landfills (*landfill*), (3) wood burned to generate energy (*energy*), and (4) wood burned without producing energy and wood decomposition (*emissions*).

2.1.2. Development of FORCARB-ON based on FORCARB2

To adapt FORCARB2 to Ontario forests, we (1) added a module to account for the effects of fire disturbance on forest C, (2) developed a stand-alone HWP C model using the same methodology and parameters used in the HWP module in FORCARB-ON, which simplified model operations when estimating HWP C from historic harvest and harvest from private lands, and (3) re-parameterized the model using data from studies conducted in and near Ontario. The

Table 1
(a) Equations used to calculate C in FORCARB-ON (equations for calculating wood and wood products C are not included) and (b) parameter definitions.

(a) Equations:

Carbon pool	Equation	
Live tree	$B_{li} = L_1 \times (L_2 + 1.0 - \exp^{-(V_d/L_3)})$	(1)
Standing dead tree	$B_{sd} = B_{li} \times S_1 \times \exp^{-(V_d/S_2)^{S_3}}$	(2)
Fire-caused standing dead tree	$B_{sd1} = B'_{sd1} \times \exp^{-L_p \times R_{sddcy}}$	(3)
Down dead wood[a]	$B_{ddw} = M_{old} + M_{new}$	(4)
Forest floor	$B_{ff} = \frac{F_1 \times Y_{CT}}{F_2 + Y_{CT}} + F_3 \times \exp^{-(Y_{CT}/F_4)}$	(5)
Understory vegetation	$B_{und} = U_0 + U_1 \times Y_{CT} + U_2 \times Y_{CT}^2$	(6)

(b) Parameters:

- B_{li}—live tree biomass density ($\mathrm{t\,ha^{-1}}$)
- L_1, L_2, and L_3—live tree biomass parameters given by forest region, type, and ownership
- V_d—merchantable volume density ($\mathrm{m^3\,ha^{-1}}$)
- B_{sd}—standing dead tree biomass density ($\mathrm{t\,ha^{-1}}$)
- S_1, S_2, and S_3—standing dead tree biomass parameters given by forest region, type, and ownership
- B_{sd1}—Standing dead tree C in areas burned in previous periods that decays to the current value ($\mathrm{t\,ha^{-1}}$)
- B'_{sd1}—Total standing dead tree C in areas burned in previous periods that decays to the value before the present period ($\mathrm{t\,ha^{-1}}$)
- L_p—the number of years in each period
- R_{sddcy}–the decay rate of fire-killed standing trees
- B_{ddw}–down dead wood biomass density ($\mathrm{t\,ha^{-1}}$)
- M_{old}–biomass density of old down dead wood that decays to the current value:
  $M_{old} = M'_{ddw} \times e^{-(L_P/R_{dcy})}$
  where M'_{ddw} is the biomass density of down dead wood in the previous simulation period and R_{dcy} the decay rate of down dead wood
- M_{new}—biomass density of the down dead wood created in the present simulation period ($\mathrm{t\,ha^{-1}}$)
- B_{ff}—forest floor biomass density ($\mathrm{t\,ha^{-1}}$)
- F_1 and F_2—coefficients that relate forest age and forest floor C; F_3–average post-harvest forest floor C density; F_4–forest floor decay factor
- Y_{CT}—average age of a age class of trees
- B_{und}—biomass density for understory vegetation ($\mathrm{t\,ha^{-1}}$)
- U_0, U_1, and U_2—coefficients for understory vegetation C calculation

Note: Soil C density is assumed constant by forest type and region (Heath et al., 2001), and is not included in this table.
[a] For details of down dead wood calculation, refer to Heath and Chojnacky (2001) and Chojnacky and Heath (2002).

revised model and added components were integrated into a Windows® application, named FORCARB-ON. Fig. 1 shows the main components of FORCARB-ON and their interconnection, and Fig. 2 illustrates the model's general structure.

2.1.3. Forest development simulation used in C stock projection

FORCARB2 was built to be parallel with the U.S. inventory model ATLAS (Mills and Kincaid, 1992) to simulate forest C budgets using readily available data such as forest area, timber volume, and removals, from the latter as inputs. ATLAS, the U.S. national timber supply model, was linked with a series of other models to produce long-term timber supply and demand projections for legislated long-term forest planning needs (e.g., see Haynes et al., 2007). Linking FORCARB2 to this modeling system allowed C estimates to be consistent with forest volume estimates.

In FORCARB-ON (Figs. 1 and 2), we replaced ATLAS with the Strategic Forest Management Model (SFMM) (Kloss, 2002), the principal model used in forest management planning in Ontario. SFMM simulates forest development at a management unit scale, in which a forest management unit is divided into *forest units* (groups of forest stands with similar tree species that develop in a similar way and are managed with the same silvicultural system). It projects forest information through time based on an initial forest state derived from forest resources inventory, forest dynamics (natural succession, fire disturbance, growth and yield curves, and potential for wildlife habitat), silvicultural options (for harvesting, renewal, tending and partial harvesting), and management objectives (diversity of future forest, desired future forest condition, wood supply, financial resources, etc.). SFMM simulates forest development normally at 10-year time steps (i.e. a term) and 150 years into the future. Research was conducted in natural forest succession to determine natural succession rules for a given forest management unit in forest management planning (Kenkel et al., 1998; Vasiliauskas et al., 2004). Growth and yield curves used in most forest management plans were derived from Plonski's curves (Plonski, 1981), which were refined in recent studies (Vasiliauskas et al., 2004; Penner et al., 2008). Fire return intervals vary significantly in the managed forests in Ontario: from 100 to 500 years in the northwest to 1000–5000 years in the northeast to greater than 5000 years in southern Ontario (OMNR, 2004). Aggressive fire suppression in forest management units, as well as major parks, had led to considerably lengthened fire return intervals in these forests (Ward et al., 2001). Forest management planning teams use regional fire history to produce a specific fire return interval for each management unit, and based on which an annual burning proportion is applied to all forest age classes in a SFMM simulation. SFMM applies linear programming to solve the optimization problem in finding the maximum available harvest area under the constraints induced by the various natural and management factors. In Ontario, forest management plans are required by law to be updated every five years, with a new SFMM simulation updated by field data such as that for harvest and fires, as well as the latest forest resources inventory information, if available.

2.1.4. Harvested wood product C estimation

Harvesting transfers merchantable wood from forests to mills, where a portion is processed into HWP. The detailed methodology that we used for HWP C estimation, as well as HWP C estimates, was reported in Chen et al. (2008); thus, we provide only a summary here. To estimate C flows after harvesting, FORCARB-ON converts the removed wood volume into C and then partitions the C among the four HWP end-use categories. A product age-based C distribution matrix was used to allocate the C; it describes initial C distribution among the primary HWP types, C losses along the process chain, and the movement of C over time among the end use categories to reflect the service life of HWP, decomposition, end-of-life disposal, and the decomposition of wood buried in landfills. We developed the Ontario version of the distribution matrix for FORCARB-ON based on Ontario data to reflect harvested forest types, hardwood/softwood volume distribution among primary

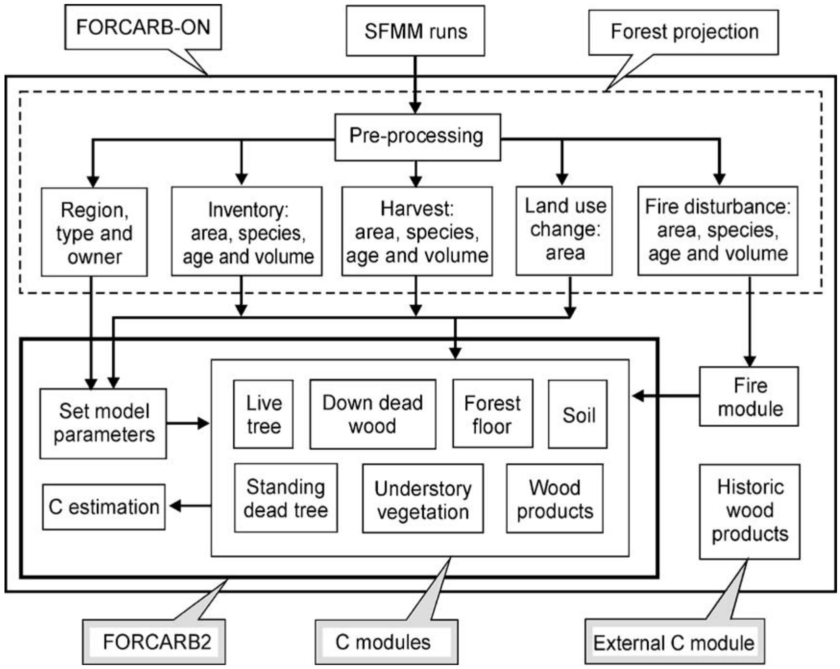

Fig. 1. Flow chart for FORCARB-ON and FORCARB2 simulation. Arrows indicate the direction of data flow. SFMM, an external application, produces a description of present and future forest structure (age class and species). In theory, SFMM can be replaced by other timber supply models. Carbon (C) is estimated in FORCARB2 C-conversion modules. Carbon flow among FORCARB2 C modules is not shown.

forest products (sawlogs, composite panels, pulpwood, and fuelwood), processing methods and conversion efficiencies, end use HWP type and service life, landfill HWP decomposition and carbon stocks, and HWP trade (Chen et al., 2008).

2.2. Developing the fire module for FORCARB-ON

2.2.1. Forest fire disturbance in Ontario and the fire module development

Effects of harvesting on forest and HWP C are simulated in FORCARB2 (Heath and Birdsey, 1993b; Smith and Heath, 2004; Heath and Skog, 2004), but fire impacts are not explicitly simulated. In Ontario, the boreal forest comprises 50 million of the total 71 million ha of forest, and the hardwood and mixedwood dominated Great Lakes-St. Lawrence Forest comprises 20 million ha (OMNR, 2007). In the boreal forest, fire is an important natural disturbance that significantly affects forest C (Amiro et al., 2001; Rothstein et al., 2004). An average of 55,000 ha of the managed boreal forest is burned each year, compared with 2100 ha of annual burn in the Great Lakes-St. Lawrence forest (OMNR, 2007). Therefore, we added a fire module to FORCARB-ON, which used a C flux matrix for fire disturbance (Table 2) to calculate C flows among various forest ecosystem C pools and C released to the atmosphere through combustion. This C flux matrix was developed based on published data for North America, using primarily data from Ontario and adjacent areas with similar forest conditions as summarized in the following sections (Sections 2.2.2–2.2.4).

2.2.2. Direct live tree C loss through combustion

Our literature review suggests that even fairly intense fires only consume most of foliage, small branches, and a fraction of the surface organic layer; while other biomass pools are killed but are predominantly not consumed in the fire, thus entering the dead biomass pools (Stocks, 1989; Hendrickson, 1990; Stocks et al., 2004). On average, 95% of fuels consumed during a crown fire in a jack pine-black spruce forest in Canada's Northwest Territories were needles and branches smaller than 1 cm in diameter (Stocks et al., 2004). In a study of several jack pine stands after stand

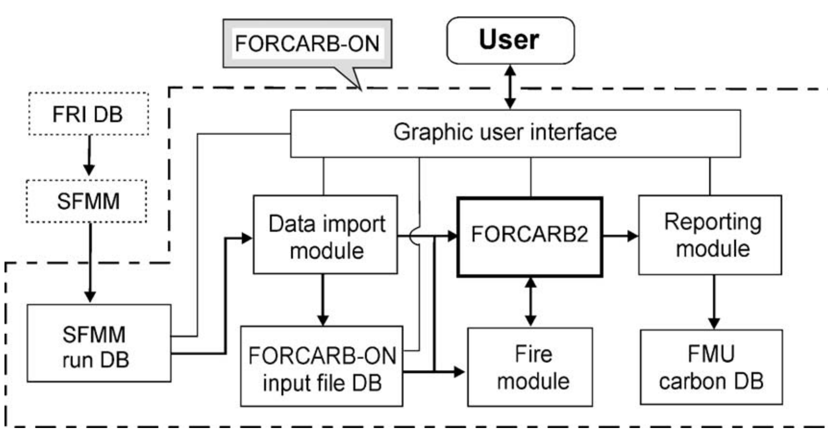

Fig. 2. Structure of FORCARB-ON, the version of FORCARB2 modified for use in Ontario. The symbols used in the diagram (the external wood product module for historic harvesting not included) are: dashed box: components outside of FORCARB-ON. solid box: FORCARB-ON components. arrow: direction of data flow. FRI DB: forest resources inventory database. SFMM: Strategic Forest Management Model. FMU: forest management unit.

Table 2
Fire disturbance carbon flux matrix for Ontario forests (describing the movement of carbon among pools in the year following disturbance by fire since 2001).

Pre-disturbance	Post-disturbance									
	Standing dead tree						Forest floor	Soil	Emission	Charcoal
	Softwood		Hardwood		Down dead wood					
	Aboveground	Belowground	Aboveground	Belowground	Softwood	Hardwood				
Live tree										
Softwood/aboveground	0.765	0	0	0	0.03	0	0.018	0	0.174	0.013
Softwood/belowground	0	0.903	0	0	0	0	0.073	0	0.024	0
Hardwood/aboveground	0	0	0.839	0	0	0.029	0.007	0	0.123	0.002
Hardwood/belowground	0	0	0	0.903	0	0	0.073	0	0.024	0
Standing dead tree										
Softwood/aboveground	0.733	0	0	0	0.128	0	0	0	0.138	0.001
Softwood/belowground	0	0.807	0	0	0	0	0	0.108	0.084	0.001
Hardwood/aboveground	0	0	0.724	0	0	0.137	0	0	0.138	0.001
Hardwood/belowground	0	0	0	0.802	0	0	0	0.108	0.089	0.001
Down dead wood										
Softwood	0	0	0	0	0.844	0	0	0	0.076	0.08
Hardwood	0	0	0	0	0	0.844	0	0	0.076	0.08
Forest floor	0	0	0	0	0	0	0.565	0	0.413	0.022
Understory	0.1	0.05	0.1	0.051	0	0	0	0	0.665	0.034
Soil	0	0	0	0	0	0	0	0.965	0.035	0
Charcoal	0	0	0	0	0	0	0	0	0	1

replacing fire, direct forest C loss to combustion after stand replacing fires varied from 5% to 25% (Rothstein et al., 2004). Amiro et al. (2001) estimated an average loss of 13 t C ha^{-1} of burned area across Canada.

By averaging estimates from Ker (1980), Freedman et al. (1982) and Jenkins et al. (2003), we estimated that foliage comprises 13.7 and 4.5% of softwood and hardwood aboveground biomass, respectively. Branches were similarly estimated to comprise, 18.5 and 39.2% of softwood and hardwood aboveground biomass, respectively. We assumed that 20% of branch biomass is in branches smaller than 1 cm in diameter and that they would be consumed in a forest fire, with 100% of their C released to the atmosphere. Thus, 3.7 of softwood and 7.8% of hardwood aboveground biomass would be directly lost to combustion. de Groot et al. (2003) concluded that most area burned in North America boreal forests was by high intensity crown fires that burned all foliage. Thus, for simplicity's sake, we assumed all foliage was combusted by forest fires and estimated the total direct C loss to fires from aboveground biomass as 17.4 and 12.3% of softwood and hardwood, respectively. Fine roots account for about 18 to 20% of root biomass (Cairns et al., 1997; Jenkins et al., 2003; Li et al., 2003), and we assumed that a small portion of them in the forest floor would be burned during a fire (consuming 2.4% of belowground live tree C).

2.2.3. Direct C loss from burning standing dead trees, down dead wood, forest floor, and understory vegetation

We summarized estimates from Stocks (1989), Vose et al. (1999), Tinker and Knight (2001), and Stocks et al. (2004), and estimated C loss rates of 7.6% and 41.3% for down dead wood and forest floor, respectively. Because of the lack of published data on the percentages of standing dead tree C that burns and is released to the atmosphere, we assumed that these trees had only large branches and tree boles and that 13.8 and 8% of their above- and belowground C, respectively, was released to the atmosphere by fire. Using data from Kasischke et al. (2005), we estimated that 33.5% of understory biomass was lost directly to fire.

2.2.4. Post-fire C stock estimation for standing dead tree, down dead wood and forest floor pools

Standing dead tree, down dead wood, and forest floor C in burned areas was calculated using the C flux matrix for fire disturbance and tracked as trees regenerate and grow. Forest floor C consists of two components (Table 1, Eq. (5)): average post-harvest forest floor C that decays over time and additions to forest floor C from regenerating trees. For burned forest, forest floor C was estimated based on combustion of a fraction of the pre-burn forest floor C. Down dead wood also consists of two parts: down dead wood in the previous simulation period that decays to the current value and down dead wood added in the current period. Post-fire down dead wood C density values were estimated based on combustion of a fraction of the pre-burn down dead wood C.

Following Smith et al. (2003), the standing dead tree C density was estimated primarily by fitting nonlinear regressions to the plot-level ratios of standing dead tree mass to the estimated live tree mass (Table 1: Eq. (2)), resulting in minimum standing dead tree C for age class 1 due to the minimal volume of live trees at the time of stand development. In burned stands, more than 80% of live tree C is transferred to the standing dead tree pool. To track C in fire-killed standing trees over time since fire, we used Eq. (3) in Table 1. We applied a simplified assumption that the C in the fire-created standing dead trees remains in this pool with C released to the atmosphere through decomposition. Therefore, C transfers from fire-killed standing trees to other pools (mostly down dead wood) were not simulated. We used a decay rate constant of 0.15 for fire-origin standing dead trees, compared with 0.096 used by Rothstein et al. (2004). Thus, our decay rate for standing dead trees could underestimate standing dead tree C. But when standing dead trees fall (usually within a decade), they add most of their C to the down dead wood pool (Mitchell and Preisler, 1998; Lee, 1998). Down dead wood decomposes much faster and may decompose completely within 35 to 45 years (Laiho and Prescott, 1999). We assumed that the decomposition of down dead wood followed an exponential equation (Table 1), and on average, 90% of all down dead wood was assumed to decompose in 50 years. The decay rate (0.15) that we used in the simplified calculation for fire-created standing dead trees combined the decay rates of standing dead trees in the initial 10 years and down dead wood thereafter, thus assuming that fire-created standing dead trees would decompose almost completely in 40–50 years. We added the standing dead tree C values calculated using this equation to the C values calculated using Eq. (2) in Table 1 to produce total standing dead tree C.

Table 3
Wood products carbon distribution matrix by year after harvest for FORCARB-ON. The proportions of the 4 end use categories in each column sum to 1.

End use category	Carbon distribution (%) by wood product age										
	10[a]	20	30	40	50	60	70	80	90	100	110
In use	0.348	0.307	0.271	0.236	0.223	0.211	0.198	0.186	0.173	0.160	0.154
Landfill	0.307	0.333	0.353	0.373	0.373	0.373	0.372	0.372	0.372	0.372	0.372
Energy	0.166	0.169	0.172	0.174	0.175	0.176	0.177	0.178	0.179	0.180	0.181
Emission	0.179	0.191	0.204	0.217	0.229	0.240	0.253	0.264	0.276	0.288	0.293

[a] Years after wood products are manufactured.

2.3. Parameterizing FORCARB-ON

The C prediction parameters we used in FORCARB-ON were based partly on FORCARB2 using values formulated for the northcentral Lake States region, including Michigan, Minnesota, New York, Ohio, and Wisconsin. All of these states border or are close to Ontario and have similar forest conditions. Some Canadian data were used in producing these parameters (Smith and Heath, 2002; Jenkins et al., 2003). We adjusted FORCARB2 parameters developed for the Lake States region using more Canadian data sources for down dead wood, soil, and HWP. FORCARB2's live tree, standing dead tree, and understory vegetation C parameters set for Lake States region were used in FORCARB-ON for similar forest types, as the C densities produced for Ontario's forest types using these original FORCARB2 parameters were well within the ranges of published values for Ontario and adjacent forest areas. Because the dynamics of standing dead tree and understory vegetation C pools were less known, we assumed that they should not be the main factors of forest C stock changes and thus should be relatively stable. Model testing results showed that using FORCARB2 parameters produced generally stable C stocks for these two pools.

Table 3 presents the HWP C distribution matrix used in FORCARB-ON. The initial C distribution among the four categories was determined by the distribution of wood harvested among primary products and wood processing in Ontario (Kurz et al., 1992; Chen et al., 2008). Transfer rates of C from in use to the other categories and from landfill to emission were determined by considering HWP lifetimes and decomposition rates, waste HWP processing and fate (recycled, burned with or without energy production, or discarded in landfills), and decomposition rates in landfills (Kurz et al., 1992; Skog and Nicholson, 2000; UNFCCC, 2003; Chen et al., 2008).

A notable difference between the HWP C distribution matrices in FORCARB2 and FORCARB-ON is the much smaller allocation of harvested wood for fuelwood in Ontario. Powell et al. (1993) estimated that in 1991, 17.8% of U.S. harvested wood was directly used for fuel, while Skog and Rosen (1997) reported that in the same year, 19% of the U.S. roundwood harvested was used directly for fuel. In addition, residue from primary wood processing used as fuel accounted for another 17% of the total roundwood harvested. In Ontario, in comparison, fuelwood harvest from 2000 to 2005 was only 0.60% of the total roundwood harvest (Canadian National Forest Database Program, available at www.nfdp.ccfm.org/compendium/data/2007_10/tables/com51e.htm, accessed 3 June 2008). Therefore, with FORCARB-ON, less C is present in the energy category and more is in other categories than with FORCARB2 (Chen et al., 2008).

Soil C densities for common Ontario forest species groups in FORCARB2 (Heath et al., 2003) were reparameterized in FORCARB-ON (Table 4). Soil C densities in FORCARB2 are higher than in FORCARB-ON because of the different soil databases used: soil C parameters in FORCARB2 were derived from the STATSGO soils database (Heath and Smith, 2000; Heath et al., 2001), and those in FORCARB-ON are based on Canadian field data (Siltanen et al., 1997). The soil C densities in FORCARB2 include histosols (USEPA, 2008), whereas those in FORCARB-ON do not. Despite large differences in soil C parameters between FORCARB-ON and FORCARB2, changes in forest soil C stocks over time in either model will be negligible, so long as species composition remains similar.

Table 4
Soil carbon (C) densities used in FORCARB-ON and FORCARB2 for select common Ontario forest species groups.

Model	Soil C by species group (t ha^{-1})			
	White-red-jack pine	Aspen-birch	Maple-birch	Spruce-fir
FORCARB2	120.8	146.1	134.3	261.8
FORCARB-ON	44.0	61.0	108.4	58.2

2.4. Ontario's managed forests and methods for C estimation

2.4.1. Forest management types in Ontario

Ontario's Crown forests managed for timber production cover 28.8 million ha and are divided into 46 forest management units (Fig. 3). These units are managed by individual forest companies following regulations of Ontario's Ministry of Natural Resources for sustainability. Before any forestry activities can take place in a management unit, an approved forest management plan must be in place. We produced a C budget for each of the 46 management units using data extracted from SFMM simulations used in forest management plans available at the time of analysis (the oldest SFMM simulations were from 1998). The three other types of managed forest in Ontario are parks (4.1 million ha), measured fire management zones (3.4 million ha), and privately owned forests (6.0 million ha). In forest management units and major parks, aggressive fire suppression operations have been conducted to extinguish fires at small sizes and minimize area burned. In measured fire management zones, however, if the initial suppression efforts fail, an assessment is made of the growth potential of the fire, the values at risk, and the cost of continuing aggressive suppression. This assessment may result in a range of actions, from continuing aggressive suppression to withdrawal of suppression forces and observation of the fire (Ward et al., 2001). Parks and measured fire management zones are Crown forests and are not subject to harvest. Private forest lands are located across the province and are harvested for timber at the landowner's discretion.

No SFMM model simulations have been conducted for parks, measured fire management zones and private lands. Therefore, C budgets for these areas were produced by extrapolating the present and future forest condition of similar forests in adjacent management units. We added these C budgets to that of the management units to produce a total C budget for all managed forests in Ontario.

2.4.2. Method for estimating forest C stock for parks

For parks larger than 1000 ha, the C densities of the *reserved forests* (areas within Crown forest management units not harvested but subject to fire suppression) of the adjacent management units

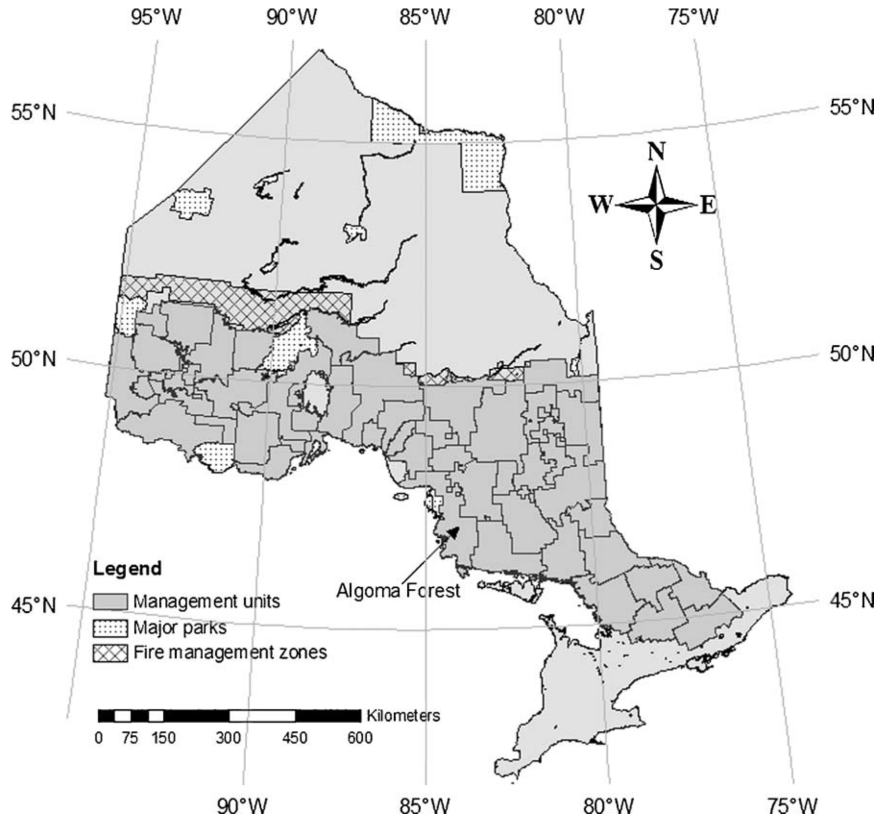

Fig. 3. Administrative boundaries of Ontario's 46 forest management units (as of April 1, 2009), large parks, and measured fire management zones. *Note:* The light grey area in Ontario's far north consists of forests and peatlands; the forests in the vast area is not managed, and thus not included in the present study.

were used to produce an area-weighted average C density; carbon projections of these managed forest areas were then produced by multiplying the average C densities by their areas. To produce a C budget for the many small parks across the province, we used the total area of small parks multiplied by the area-weighted average C densities of the reserved forests from all 46 management units. For all parks, we assumed 10% of the total area was water (OMNR, 2007), and this area was excluded from C estimation.

2.4.3. Method for estimating forest C stock for measured fire management zones

For measured fire management zones, we assumed that their forests were similar to the available forests in the adjacent forest management units in their immediate south in terms of species compositions, natural succession, and growth and yield. But age class structure in measured fire management zones may be different from both the reserved and available forests (forests that are available for timber harvesting) of the adjacent management units. The average age class in the reserved forests in the adjacent management units is likely greater than that in the measured fire management zones, because reserved forests have not been harvested while receiving aggressive fire suppression. The average age class in the available forests, on the other hand, may be smaller than that from the measured fire management zones, because harvest targets on the mature forests compared to fires that burn all age classes. Therefore, the only possible estimate of forest C for the measured fire management zones was that of a long-term average value. We produced such an average value based on the facts about or assumptions we made for the measured fire management zones: a) there was no harvest, b) the limited fire protection did not significantly change annual area burned (Ter-Mikaelian et al., 2009), and c) the natural fire regime has not changed in the past a few decades (Ter-Mikaelian et al., 2009). We used the natural fire return intervals estimated for the forests in or around the measured fire management zones to rerun the SFMM simulations for the adjacent forest management units. For the northeast portion of the measured fire management zones, the fire return interval was adjusted to 263 years (Ter-Mikaelian et al., 2009). For the northwest portion 90 years was used (Ward et al., 2001). The resulting average C density of the reserved and available forests from the adjacent FMUs became stable from 2070-2100. The forest C stocks in the measured fire management zones were calculated as a long-term average using the average of the reserved and available forests C densities at 2100.

2.4.4. Method for estimating forest C stock for private forests

To produce C estimates for private forest lands, we estimated the proportions of the area subject to harvest vs. not, and applied the average C densities of the available and the reserved forests from adjacent management units, respectively.

2.4.5. Estimation of C stock in HWP

Harvested wood products C stocks and emissions during 2001–2100 were projected for present and future harvesting (2001–2100) and historical harvesting (1951–2000) using the FORCARB-ON wood product module. Harvested wood products in use prior to 1951 were not included in this estimate, because harvest data were unavailable. Regardless, HWP from pre-1951 harvest only minimally affect total C stock changes for the period 2001–2100 (Chen et al., 2008). There were no harvest projections available for private forests between 2001 and 2100. But private forest lands account for 12% of the productive forests in Ontario and produced 14% of the provincial harvested wood from 1999 to 2003 (OMNR, 2007, p. 651, Table 7.3.2d) and approximately 20% prior 1999 (OMNR, 2002, p. 3–152). Thus, we assumed that wood harvested from private lands will account for 12% of the provincial total in the period

Table 5
Carbon (C) budget of the Algoma Forest Management Unit, 2001-2100 (in Mt), estimated using FORCARB-ON.

	Year										
	2001	2011	2021	2031	2041	2051	2061	2071	2081	2091	2101
Live tree	28.2	30.1	31.1	31.0	30.5	29.7	28.9	28.3	28.0	27.9	27.8
Standing dead tree	3.4	3.5	3.5	3.5	3.4	3.4	3.3	3.2	3.2	3.2	3.2
Down dead wood	3.3	3.5	3.7	3.8	4.0	4.0	3.9	3.9	3.8	3.8	3.8
Soil	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9
Forest floor	12.5	12.7	13.0	13.1	13.2	13.3	13.3	13.4	13.4	13.5	13.5
Understory	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Total	86.0	88.6	89.9	90.1	89.8	89.0	88.2	87.5	87.2	87.1	87.0
C density ($t\,ha^{-1}$)	184.0	189.4	192.3	192.8	192.1	190.6	188.9	187.6	186.9	186.7	186.7
Wood product C[a]	0.0	1.0	1.8	2.8	3.8	4.7	5.7	6.6	7.4	8.2	9.1

[a] Wood product C from historical harvesting (1951–2000) not included.

2001–2100 to match the proportion of productive forests that they account for.

3. Results

3.1. Carbon budget of the Algoma Forest Management Unit

We present the Algoma Forest Management Unit (Fig. 3) as an example of how forest C varies with forest structure. We used the current forest conditions and future development predicted in the 2000 Forest Management Plan of this management unit simulated using SFMM. The Algoma Forest covers 468,000 ha of northeastern Ontario, and is within the Great Lakes-St. Lawrence forest area. Each year about 5500 ha (1.2% of the area) are available for harvest. As it is in the Great Lakes-St. Lawrence Forest region where forests have long fire return intervals and receive aggressive fire suppression, the projected long-term natural disturbance by fire is only about 4 ha per year. Dominant species include hard maple (primarily sugar maple, *Acer saccharum* Marsh.) (46% of area) and white birch (*Betula papyrifera* Marsh.) (15% of area). Hard maple is present in all age classes up to 200 years, but most is 61–120 years old. White birch is present in all age classes up to 140 years old, but most is 40–80 years old. The remaining forest area is composed of species groups termed "other conifer" and "other hardwood."

Between 2001 and 2100, the forest ecosystem C stock in Algoma Forest Management Unit is projected to change from 86.0 Mt in 2001 to 87.0 Mt in 2100, a projected 1.0 Mt C sink (not including HWP) (Table 5). The greatest forest ecosystem C stock is projected to occur in 2031 when it peaks at 90.1 Mt, and the least in 2001 at 86.0 Mt. Average forest C density was projected to increase from 184.0 $t\,ha^{-1}$ in 2001 to 186.7 $t\,ha^{-1}$ in 2100, peaking at 192.8 $t\,ha^{-1}$ in 2031 (Table 5).

Soil C pool was projected to be the largest one in the forest (37.9 Mt), and near constant throughout the simulation because only small forest type changes were predicted to occur. Live tree C is the second largest forest C pool, with C varying between 27.8 and 31.1 Mt. Carbon in down dead wood and standing dead tree pools were predicted to vary between 3.3 and 4.0 Mt and 3.2 and 3.5 Mt, respectively. Understory vegetation C was the smallest forest stock at around 0.8 Mt. Carbon in HWP in use and in landfills, from harvesting between 2001 and 2100 in the Algoma Forest, was projected to increase by 8.6 Mt.

Fig. 4 illustrates how forest ecosystem C stock, merchantable volume, and mean forest age (years) change over time. The forest ecosystem C stock was projected to closely follow the pattern of the changing merchantable volume, but change of forest ecosystem C did not closely follow the changes of mean forest age in the simulation.

The live tree pool size primarily reflects changes in age structure and species composition, and in absolute values was the most dynamic pool (on a percent change basis the most dynamic pool was down dead wood C). Changes in live tree C are most responsible for changes in forest management unit C. Live tree C is calculated from and positively related to net merchantable volume (Eq. (1) in Table 1), and merchantable volume is determined by age structure and species composition. Thus, changes in live tree C, as well as forest ecosystem C, are related to changes in total net merchantable volume (Fig. 4). Mean forest age is less relevant to live tree and forest ecosystem C stock changes

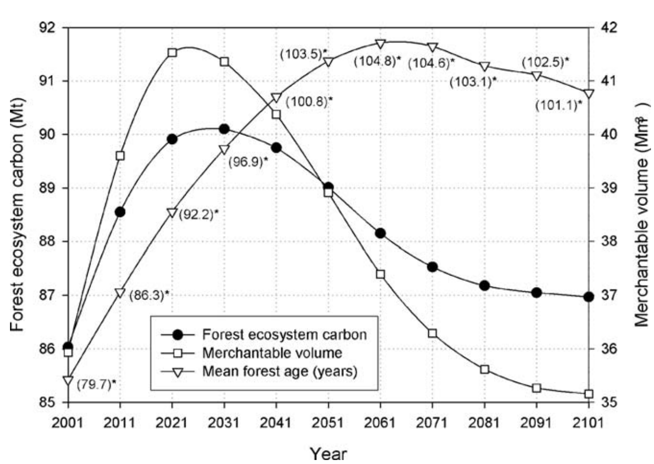

Fig. 4. Forest ecosystem carbon (C) changes in relation to the changes in inventory net merchantable volume in the Algoma forest management unit. *Numbers in parenthesis are mean forest ages predicted for the Algoma Forest at the end of each decade.

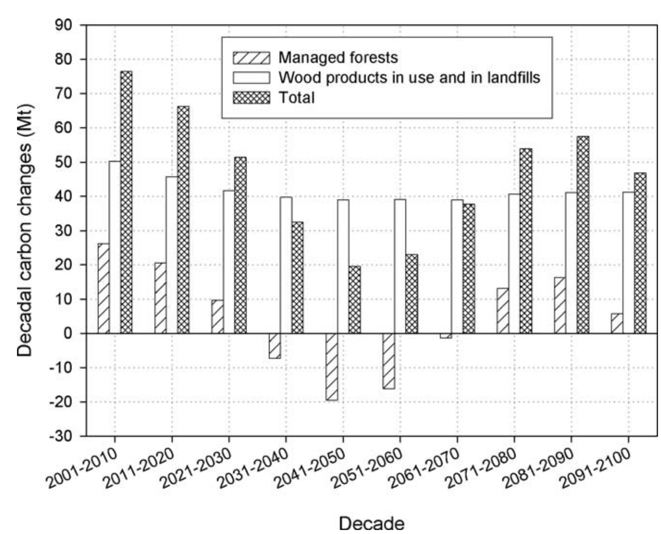

Fig. 5. Projected decadal changes in carbon stocks in managed forest ecosystems and in wood products in use and in landfills during 2001–2100.

Table 6
Carbon stocks in Ontario's managed forests and HWP (in use and in landfills) from 2001 to 2100 (in Mt), estimated using FORCARB-ON.

Year	2001	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	Total change[c]
Forest management units	4278.3	4275.2	4278.3	4282.9	4283.6	4279.4	4276.0	4278.9	4286.5	4292.9	4291.5	13.2
Measured fire management zones[a]	556.1	556.1	556.1	556.1	556.1	556.1	556.1	556.1	556.1	556.1	556.1	0.0
Parks[a]	579.3	590.2	596.6	598.3	595.4	589.1	583.4	581.8	585.7	591.7	595.9	16.6
Private forest land[a]	795.5	814.1	825.2	828.7	823.5	814.5	807.4	804.7	806.5	810.6	813.6	18.1
Total in forests (forest management units + fire management zones + parks + private forest land)	6209.2	6235.6	6256.2	6266.0	6258.6	6239.1	6222.9	6221.5	6234.8	6251.3	6257.1	47.9
Historical wood products (1951-2000)	125.8	122.2	118.5	115.1	112.0	109.4	107.1	105.4	104.0	102.5	101.5	-24.3
Future wood products from managed Crown forests (2001-2100)	0.0	47.4	91.0	130.6	168.3	205.0	241.4	277.1	314.2	351.6	388.7	388.7
Future wood products from private forests (2001-2100)[b]	0.0	6.5	12.4	17.8	22.9	27.9	32.9	37.8	42.8	47.9	53.0	53.0
Total wood products (historical + future)	125.8	176.0	221.8	263.5	303.2	342.2	381.3	420.3	460.9	502.0	543.2	417.4
Total managed forest and wood product carbon	6335.0	6411.7	6478.0	6529.5	6561.9	6581.3	6604.2	6641.8	6695.8	6753.4	6800.3	465.3

Note: Table reproduced primarily from Colombo et al. (2007). A research information note of Ontario Ministry of Natural Resources; we added harvest estimates from private forests in 2001–2100, and updated estimates for measured fire management zones.
[a] Carbon estimates for parks and private forest land were extrapolated from adjacent management units; carbon for measured fire-management zones was presented as a long-term average based on assumptions in Section 2.4.3.
[b] Wood products from harvesting Ontario's private forests in 2001–2100 were estimated as 12% of the provincial total.
[c] Total change refers to the difference of carbon storage in 2001 and 2100.

Table 7
Harvested wood product carbon storage and emissions (Mt) by decade from historic (1951–2000) and current/future harvest (2001–2100) from Ontario's managed forests, estimated using FORCARB-ON[a].

Year	2001	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Historic harvest											
In use	44.2	39.2	35.1	32.0	30.0	28.3	26.6	25.0	23.5	21.9	20.7
Landfill	81.6	83.0	83.4	83.1	82.0	81.1	80.5	80.4	80.5	80.6	80.7
Energy	42.8	43.1	43.4	43.6	43.8	43.9	44.0	44.2	44.3	44.4	44.5
Emission	45.5	48.8	52.1	55.3	58.2	60.8	62.9	64.5	65.8	67.1	68.0
Current/future harvest[b]											
In use	0.0	28.6	52.2	71.3	87.3	102.5	117.4	131.4	145.8	159.8	173.1
Landfill	0.0	25.3	51.2	77.1	103.9	130.4	156.9	183.5	211.2	239.7	268.6
Energy	0.0	13.7	26.8	39.3	51.6	64.0	76.6	89.2	102.6	116.4	130.4
Emission	0.0	14.7	29.6	44.5	60.2	76.6	93.9	112.2	131.9	152.9	175.0
Total											
In use	44.2	67.8	87.3	103.3	117.3	130.8	144.0	156.4	169.3	181.7	193.8
Landfill	81.6	108.3	134.6	160.2	185.9	211.5	237.4	263.9	291.7	320.3	349.3
Energy	42.8	56.8	70.2	82.9	95.4	107.9	120.6	133.4	146.9	160.8	174.9
Emission	45.5	63.5	81.7	99.8	118.4	137.4	156.8	176.7	197.7	220.0	243.0

Note: Harvested wood product carbon is distributed among 4 categories: (1) in use, (2) landfill, (3) energy (burned to generate energy), and (4) emission (from non-energy use burning and decomposition).
[a] Table reproduced primarily from Chen et al. (2008), but with HWP carbon from harvesting Ontario's private forests in 2001–2100 included.
[b] Harvested wood products from harvesting Ontario's private forests were estimated as 12% of the provincial total.

Table 8
Carbon stocks and densities for forest ecosystem carbon pools by forest land management category in Ontario in 2001.

	Area ($\times 10^6$ ha)	Carbon storage ($\times 10^6$ t) Live tree	Standing dead tree	Down dead wood	Forest floor	Understory	Soil	Total carbon	Carbon density of management type (t ha^{-1})
Forest management units	28.7	1498.9	191.4	177.6	662.7	58.6	1689.3	4278.3	148.9
Measured fire-management zones	3.4	205.6	30.2	19.0	105.7	5.3	190.4	556.1	161.7
Private forest land	6.0	291.0	35.7	34.2	108.7	8.7	317.3	795.5	132.6
Parks	4.1	210.1	26.3	25.3	91.4	7.0	219.1	579.3	141.6
Total of all management types	42.2	2205.5	283.5	256.1	1053.2	179.9	2231.0	6209.2	146.9
Carbon density of each pool (t ha^{-1})		52.2	6.7	6.1	22.9	1.9	57.2		
Proportion in total carbon (%)		35.5	4.6	4.1	15.6	1.3	38.9	100.0	

(Fig. 4), because mean forest age is not always a good indicator of age structure and net merchantable volume.

3.2. Carbon budget of managed Ontario forests and wood products

Forest ecosystem C stock of all types of managed forests (i.e. forest management units, parks, measured fire management zones, and private lands) is projected to be a moderate to small sink in most decades, and an overall C sink of 47.9 Mt C between 2001 and 2100 (Fig. 5, Table 6). The largest portion of the forest ecosystem C storage is in the 46 management units (4278.3 and 4291.5 Mt in 2001 and 2100, respectively), because of their large area. The remaining C storage was fairly evenly divided among the other three types of managed forests.

Table 7 displays HWP C stocks and emissions in the period 2001–2100 for wood harvested from 1951 to 2100. Carbon in HWP in use and in landfills from historic harvest (1951–2000) was projected to decrease from 125.8 Mt C in 2001 to 101.4 Mt C in 2100. Meanwhile, C in use and in landfills from harvest in 2001–2100 was estimated to increase to 441.7 Mt in 2100 from zero in 2001. Overall, the HWP C stock from historic and projected future harvest was projected to increase by 417.4 Mt from 2001 to 2100 (an increase by 149.6 Mt in products in use and 267.7 Mt in products in landfills). The use of wood for energy production was projected to be 132.1 Mt C (130.4 Mt from the projected harvest in 2001–2100, 1.7 Mt from historical harvest in 1951–2000); emissions were projected to be 197.5 Mt C (decomposition and burning without energy production). Harvested wood products C stock (in use and in landfills) was the smallest total (125.8 and 543.1 Mt in 2001 and 2100, respectively), but the change had the largest projected increase compared to that of the four types of managed forests (Fig. 5). Including HWP, Ontario's managed forests were estimated as storing 6335.0 Mt C in 2001 and 6800.3 Mt C in 2100, a projected increase of 465.3 Mt C in this century.

Table 8 presents forest ecosystem C stocks by C pools, forest ecosystem C densities for each forest management type, and the C densities of each C pool of all managed forest types in 2001 (C densities for the end of each decade would be similar). Forest ecosystem C densities range from 132.6 t ha^{-1} for private forest lands to 161.7 t ha^{-1} for measured fire management zones. Soil and live tree pools C densities are the largest (57.2 and 52.2 t ha^{-1}, respectively); forest floor was also estimated as a large pool with a C density of 22.9 t ha^{-1}; standing dead tree and down dead wood stocks were fairly small amounts of C (6.7 and 6.1 t ha^{-1}, respectively), whereas understory vegetation pool had the smallest C density (1.9 t ha^{-1}). The proportion of each ecosystem C pool in the total forest ecosystem C stock of all managed forests also reflects the C densities of these C pools, with soil and live tree pools having the largest proportions (38.9 and 35.5%, respectively), and the understory pool having the smallest (1.3%).

4. Discussion

The average forest C densities for Ontario's managed forests (Table 8) that we projected using FORCARB-ON were well within the range of reported values for forests in Ontario and surrounding areas (e.g., Quebec, Manitoba, Saskatchewan, Wisconsin, Minnesota, and Michigan) with similar forest conditions (Table 9). Soil C densities in FORCARB-ON are based on field observation (Siltanen et al., 1997), which are within the range of studies by Vogel and Gower (1998) in BOREAS project forest sites in Canada and those of Grigal and Ohmann (1992) for the U.S. Lake States (Table 4). Soil C is the largest forest C pool and accounts for 38.9% of the total ecosystem C of Ontario's managed forests, with an area-weighted average C density of 57.2 t ha^{-1}.

Our estimate of average forest C density for Ontario was 146.9 t ha^{-1}, compared with 179 t ha^{-1} estimated by Liu et al. (2002). The most important factors contributing to the difference between the two estimates are:

(1) Different forest areas. Liu et al. (2002) based their estimate on Ontario's *entire* 70.6 million ha forest, while our study accounted for only the 42.2 million ha of *managed* forest.
(2) Different data sources. Liu et al. (2002) used forest inventory information from the National Forest Biomass Inventory (Bonnor, 1985), while our estimates were based on Ontario's forest resources inventory (OMNR, 2000). If forest inventories used differ in forest age and species composition, C density estimates will differ.
(3) Different models and parameters. Liu et al. (2002) used CBM-CFS2, which assumes much higher soil C densities (average of 120.0 t ha^{-1}) than FORCARB-ON does (57.2 t ha^{-1}). Meanwhile, their live tree C density is 24 t ha^{-1}, which is about half of our estimate (52.2 t ha^{-1}) and most other published values (50–60 t ha^{-1}) for Ontario and adjacent forest regions (Table 9). These differences in soil and live tree C densities are the main sources of the combined 32.2 t ha^{-1} difference in total C density (146.9 t ha^{-1} from our study and 179.1 t ha^{-1} from Liu et al., 2002).

Table 8 shows that in 2001, average C densities were projected to vary among Crown forest management units and other types of managed forests across the province, ranging from 132.6 t ha^{-1} for private forests to 161.7 t ha^{-1} for measured fire management zones. These differences were due primarily to variations in forest age structure and species composition. A younger forest might have a lower C stock but could sequester more in future decades. On the other hand, mature stands store more C, but their growth and C sequestration are slowing. Overmature forests may be small C sinks, C neutral, or even C sources because of the trees are growing more slowly with increasing stand breakup (Binkley et al., 1997; Kurz and Apps, 1999; Hyvönen et al., 2007).

Table 9
Comparison of average carbon (C) densities (t ha^{-1}) estimated using FORCARB-ON for Ontario's forest management units with published values for 6 forest carbon pools.

Data source	Live tree	Standing dead tree	Down dead wood	Understory vegetation	Forest floor	Soil	Total	Location	Note
FORCARB-ON	52.2	6.7	6.1	1.9	22.9	57.2	146.9	All Ontario FMUs	2001[d]
Bhatti et al., 2002					24–52	50–100[a]		Alberta, Canada	Boreal forest
					34–52	30–109[a]		Saskatchewan, Canada	
					21–50	57–96[a]		Manitoba, Canada	
Bhatti and Apps, 2002					32–70	37–121[a]		Ontario, Canada	Boreal forest
					24–147	21–108[a]		Quebec, Canada	
Birdsey and Heath (1995)	46.9	3.0		1.4	15.0	103.9	170.3	Northcentral US	
Birdsey and Lewis (2003)	52.7	3.4		1.1	20.9	149.1	227.3	New York, USA	1997[d]
	38.4	2.4		0.8	21.8	128.8	192.3	Minnesota, USA	
	57.7	3.7		1.3	21.8	123.9	208.3	Michigan, USA	
	48.7	3.1		1.1	19.9	124.4	197.1	Wisconsin, USA	
	62.8	4.0		1.4	20.7	114.8	203.6	Ohio, USA	
Grigal and Ohmann (1992)	57.0[b]				13.0–14.1[b]	106.0	139–234	Lake States, USA	
Liu et al. (2002)	24.1		9.5		25.4	120.0	179.1	Ontario, Canada	1999[d]
Kurz and Apps (1999)	19.7		9.9		20.7	114.6	164.8	Boreal east Canada	
Manies et al. (2005)		0.5–8.7	4.0–11.1					Manitoba, Canada	
Pedlar et al. (2002)			2.2					Northwestern Ontario, Canada	Spruce
			10.1					ibid	Aspen
			13.2					ibid	Deciduous
			20.1					ibid	Mixed
Perala and Alban (1982)		102.5[b,e]		1.6[b]	13.5[b]	33.0[b]	150.6[b]	Northcentral Minnesota, USA	Aspen
		95.0[b,e]		0.1[b]	16.5[b]	43.5[b]	155.1[b]	ibid	Spruce
		126.5[b,e]		2.2[b]	15.0[b]	48.0[b]	191.7[b]	ibid	Red pine
		90.0[b,e]		1.5[b]	16.5[b]	42.0[b]	150.0[b]	ibid	Jack pine
Siltanen et al. (1997)					23.3[c]	108.4[c]		Across Ontario, Canada	Maple-birch
					42.2[c]	58.2[c]		ibid	Spruce-fir
					23.0[c]	44.0[c]		ibid	W-r-j[f] pine
					29.6[c]	61.0[c]		ibid	Aspen-birch
Smith et al. (2004)	48.3–50.6	8.8–9.4	3.9–4.1	2.0	8.3–10.1	237.0		Lake States, US	Aspen-birch
Sturtevant et al. (1997)		1.9–9.8						Lake States, US	
Tremblay et al. (2002)					38.0–58.0	62.0		Quebec, Canada	
Vogel and Gower (1998)	27.8–58.2	2.2–8.0		2.8–3.8	4.6–11.7	18.2–52.3	72.1–119.6	Saskatchewan and Manitoba, Canada	Soil depth 15 cm
Yanai et al. (2003)					13.6			Quebec, Canada	Jack pine
					18.4[b]			Toronto, Ontario, Canada	White pine
					8.1[b]			ibid	White spruce
					3.3[b]			ibid	Paper birch
					1.2[b]			ibid	Silver maple

[a] Derived from the total soil C by subtracting the forest floor C.
[b] Converted from biomass by multiplying by a factor of 0.5.
[c] Average of all the values in the publication for the species groups occurring in Ontario.
[d] The year for which the C budgets were produced.
[e] Sum of C of live tree, standing dead tree, and down dead wood pools.
[f] W-r-j pine: White-red-jack pine.

Measured fire management zones were projected to have the greatest mean forest ecosystem C density. Because when the forest was not harvest while some fire protection was provided, the average age of the forest would increase, resulting in more wood volume to be accumulated in these zones than in other managed forests. Our projected mean C density for parks was lower than that for measured fire management zones, because we assumed only 90% of total park area was forested. If we used 90% of total area to calculate the mean forest C density for parks, the value (157.3 t ha^{-1}) approached that of fire management zones. Not surprisingly, the private forest lands were projected to have the lowest average forest C density: They are only 12% of the total productive forests in Ontario but provided 14% of the harvested wood from 1999 to 2003 (OMNR 2007, p. 651, Table 7.3.2d) and 20% prior to 1999 (OMNR, 2002, p. 3–152). Thus private forests were projected to have proportionately larger C in HWP and less in forests.

We found that HWP C was projected to increase to about 8.7 times of the 47.9 Mt C increase in forest ecosystems. In Ontario, harvest cycles are tied partly to the natural fire cycles. In Ontario's boreal forests, particularly in the northwest, fire cycles are relatively short (Bridge, 2001; Carleton, 2003). After fire, the newly produced dead woody biomass decomposes and releases greenhouse gases more quickly than do HWP, most of which are either kept in use, used to replace fossil fuels, or placed in landfills where decomposition rates are slower than those in forests.

Lumber used for residential construction, for example, is estimated to have a *half-life* (i.e., the time by which half of the C in a type of HWP has been removed from use) of 70–100 years (UNFCCC, 2003), and wood used to build homes in the United States is reported to have an 80-year half-life (USEPA, 2008).

After HWP are disposed of in landfills, the maximum decomposition proportions range from 15% for newsprint to 23% for wood to 88% for office paper (Barlaz, 1998). Because HWP decompose slowly and incompletely in landfills, our projections showed that HWP C stocks would increase over the entire simulation period, as would the combined C stocks in HWP in use and in landfills. Perez-Garcia et al. (2005), Arroja et al. (2006), Woodbury et al. (2007) and Skog (2008) all came to the same conclusion.

To assess the overall contribution of managed forests to mitigating climate change, C changes in forests must be added to the mitigation benefits from using wood to substitute for fossil fuels or other energy-intensive construction materials, and the emissions associated with the entire life cycle of HWP must also be considered. Other studies of life-cycle assessments had come to the conclusion that wood harvested from sustainably managed forests could significantly contribute to climate change mitigations through these material substitution (Scharai-Rad and Welling, 2002; Bowyer et al., 2004; Upton et al., 2007; Miner and Perez-Garcia, 2007; Sathre, 2007).

Our results support the contention that forest ecosystem C sequestration can be maintained while maintaining a continual supply of construction materials and wood energy, if the forests are managed sustainably. This strategy will not only increase C stocks in HWP in use and in landfills, but also reduce or avoid emissions indefinitely from material substitution. Perez-Garcia et al. (2005) concluded that managing forests under shorter rotations might sequester less C in forest, but the accumulating avoided and reduced emissions through substituting materials would generally be more than compensate. We hope to be able to adapt FORCARB-ON for use in studying these substitution effects in the future.

Global climate change could have important consequences for Ontario's forest ecosystems. The province's average annual temperature has been projected to increase by 4–7 °C by the end of this century (Colombo et al., 2007). This change could affect Ontario's forests both positively and negatively. For example, warming was projected to have complicated effects on forest growth, harvest, and disturbance (IPCC, 2007b). The inability to simulate these effects in SFMM, as well as in FORCARB-ON, limits our interpretation of the results of our forest and HWP C projections 100 years into the future.

To estimate future C in HWP, we had to project future HWP production and trade (Chen et al., 2008). These activities depend on many economic and political factors that are uncertain. However, our estimates were based on the best available data, and we will continue to update our projections when new data become available. For example, forest management plans in Ontario are updated in every five years with renewed forest development and harvest predictions, and we intend to update our C estimates based on these renewed projections and other new data.

In summary, we used FORCARB-ON to project that from 2001 to 2100, C in Ontario's managed forests will increase by 465.3 Mt (417.4 Mt increase in HWP in use and in landfills and 47.9 Mt increase in forests). In addition, 132.1 Mt C from the wood harvested from Ontario's managed forests in 1951–2100 was projected to be used in energy production in this century.

As the IPCC (2007c) stated, sustainable forest management combined with a sustainable supply of HWP could provide the maximum climate change mitigation benefit. Our results showed that in addition to producing a sustainable yield of timber, fibre, and energy to meet societal needs for those products, planned forest management could also maintain Ontario's managed forests as a C sink, thus generating a large sustained contribution to mitigating climate change.

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